*The Use of a Graduated Wedge in Stellar Classification and Parallax Work.* By Major William J. S. Lockyer, M.A., Ph.D. (Plate 6.)

The classification of stars according to their spectra is based on the consecutive appearance and disappearance of metallic, ionised, and gaseous lines as the stars increase or decrease their temperature. This system has proved most useful up to the present time, but there remains still a certain amount of uncertainty in the determination of spectral types. A more refined method recently adopted is that in use at the Mount Wilson Observatory, which consists in determining the *numerical* relationships between the intensities of the lines compared, thus providing a more accurate basis for the classification. This method has been recently fully set out,* and need not be described here.

In the measurement of the intensities of the spectral lines, pairs of lines, fairly close together, are selected, the negatives being placed in a stereo-comparator.

Again, the spectroscopic method of determining stellar parallaxes also involves the measurement of the relative intensities of close pairs of lines in the spectrum, for it has been found that the absolute magnitudes of the stars are closely associated with the relative intensities of the spectral lines.†

The present work of the Norman Lockyer Observatory is now devoted to both of these researches by the above-mentioned methods. The Observatory, however, does not possess a stereo-comparator or similar instrument, but has one of the small standard photo-measuring micrometers (Model 13) by Messrs. Adam Hilger. The question arose how to adapt this machine for measuring the relative intensities of the lines to which reference has been made above.

It occurred to the writer that these differences in intensities of close pairs of lines could be determined by means of a graduated neutral-tinted wedge, and, with this idea in mind, a stepped wedge was built up by cutting a homogeneously exposed Kodak film into graduated size strips and placing them one over the other after the principle of an echelon grating.

With this primitive apparatus numerous determinations of the relative intensities of pairs of lines in a spectrum were made. The results were so promising that an order was given to Messrs. Adam Hilger to supply a more refined article.

The wedge was soon received. Its gradated area measured $3{\cdot}8 \times 1{\cdot}95$ cm. It was found, however, that its densest portion was not quite opaque enough to obliterate the strongest lines in some of the spectra measured, so it was determined to procure a further one with a steeper gradient of density.

Both these wedges have now been tested, and they have given such satisfactory results that the researches referred to above have been commenced.

* *Communications to the National Academy of Sciences, Washington,* No. 23, p. 113, 1916, by Walter S. Adams.

† *Ibid.*, No. 24, p. 118, 1916, by Walter S. Adams.

The object of this paper is to describe this method now in use, since the apparatus required is simple and comparatively cheap. The method itself has the approval of Professor H. N. Russell, who, after he had examined some of the first results obtained by it, wrote as follows :—

"The method of measurement by means of a photometric wedge which he has devised is new and interesting, and the results show every evidence of great value."

Fig. 1 gives a reproduction of the wedges, and illustrates approximately their different gradations. They are each divided up by lines into twenty-five equal divisions, the width of each measuring about 0·15 cm.

In order to facilitate the measurement of the line intensities, the standard model of the Hilger micrometer had to be slightly modified, but this in no way impaired its use for ordinary measurements. The modifications were made by Messrs. Hilger. The following is a brief account of the whole apparatus as in use at the present time :—

The wedge (A) [see fig. 2] was supported on two small brackets placed at the back of the fixed frame (B), its upper surface being flush with the top of the frame. A carrier (C) was made to hold the negative and slide on the upper surface of the fixed frame (B). This carrier had at the middle of one of its long sides two legs (D) which straddled stiffly, the arm carrying both the microscope and the reflector; it was thus easily detachable. The carrier, microscope, and mirror could all be moved simultaneously by the micrometer handle (E), so that the negative passed over the wedge. Both the negative and the wedge could be viewed at the same time through the microscope.

In order not to interfere with the standard scale of the instrument, an additional scale (F) was fixed corresponding to the divisions on the wedge.

An observation consisted in moving the negative by the micrometer handle (E) until the line in the spectrum was just obliterated and then reading the number on the scale (F), estimating tenths of a division, which corresponded to that portion of the wedge that eclipsed the line.

It was found desirable to work with a more or less constant illumination, to eliminate dull or very bright days: for this purpose the micrometer was placed in a darkened cover on a table, the illumination being supplied by an electric lamp placed just outside a small orifice, the latter being covered with oiled paper.

*Test of the Gradation of the Wedges.*

In order to test the gradation of the wedges in those portions which fall directly under the optical axis of the microscope, the following procedure was adopted :—

The dense wedge was fixed in the measuring machine and a negative of $\alpha$ Leporis was placed over it in such a way that the $H\gamma$ line was in the middle of the first division in the field of view of the microscope. The light wedge was now placed on the negative, so that the first division on it was situated immediately over the $H\gamma$ line. The handle of the micrometer was now turned, thus moving the negative, light

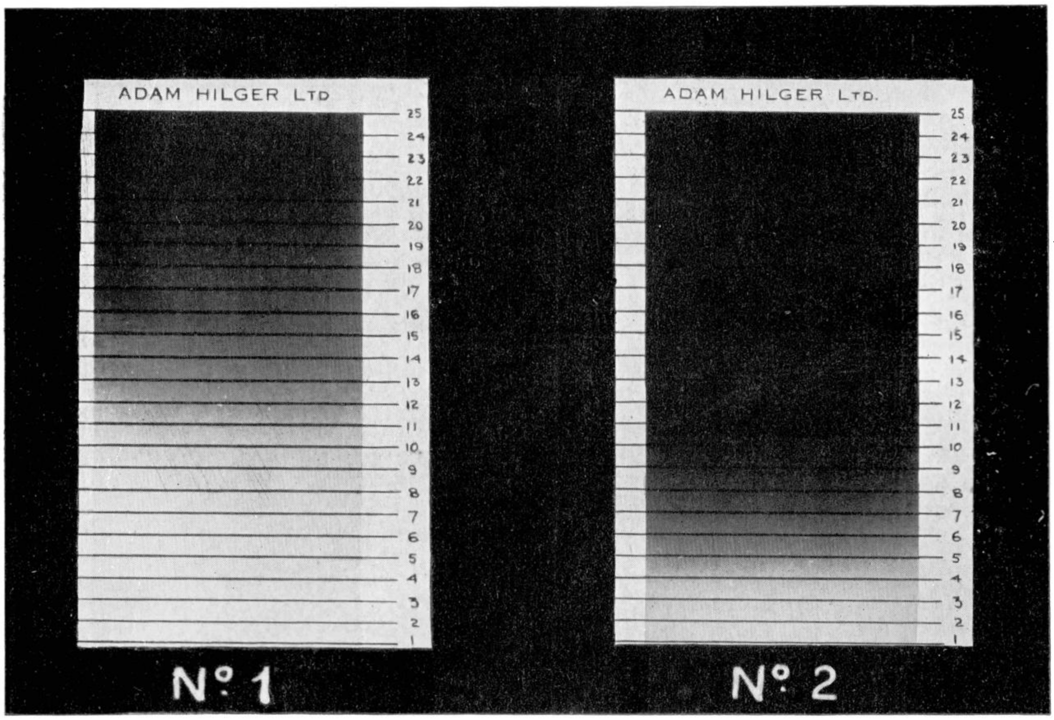
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Fig. 1.

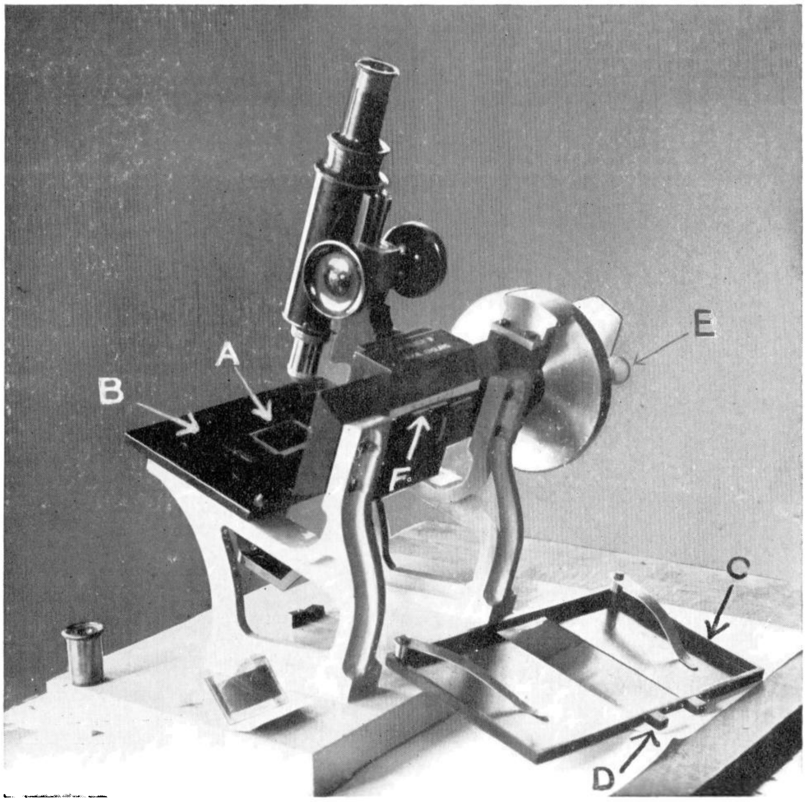
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Fig. 2.

wedge, mirror, and microscope over the dense wedge until the line became obliterated. The reading was then taken. The light wedge was now moved along the negative until the middle of the second division was over the H$\gamma$ line. The micrometer handle was again turned until the line became obliterated, and the reading taken. This process was continued for all the divisions of the light wedge.

If the wedges were equally graded the advance of one division of the light wedge should correspond to an equal advance on the dense wedge.

Two series of measures were made by two observers, namely, Mr. D. L. Edwards, chief assistant, and Mr. W. B. Rimmer, Research Student

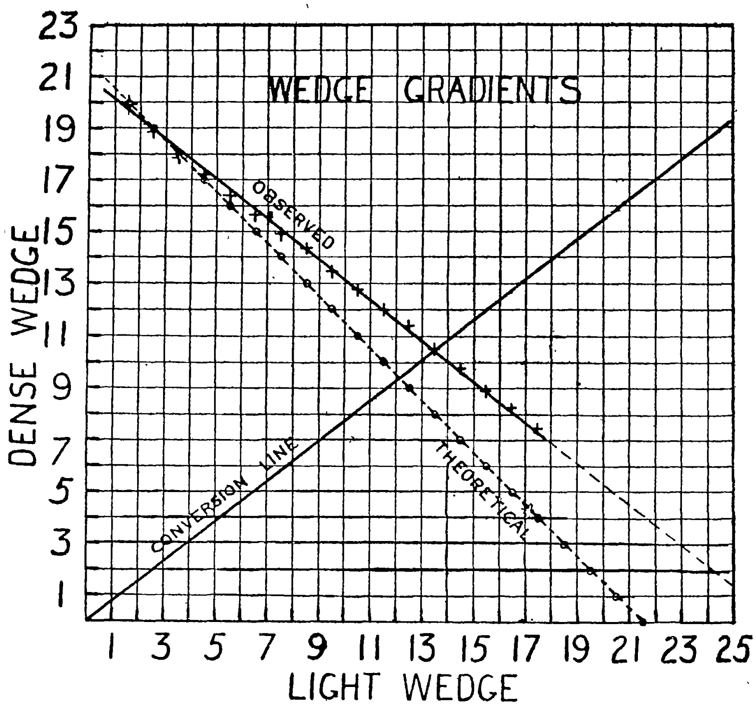


FIG. 3.

appointed by the Scientific and Industrial Research Committee. The means of each were formed, but were so similar that they were combined to form one set of measures. Fig. 3 shows the results obtained.

The broken line, marked theoretical, shows the conditions which should result from similarly gradated wedges. The continuous line with crosses shows the observed readings as the light wedge passed over the dense wedge. The observations are such that a straight line can be drawn passing very closely through the points. Such a condition indicates that the gradients of the wedge are very nearly regular, and not subject to any marked variations of density. The inclination of this line to the theoretical line shows that the gradients are not the same. Thus it will be seen that twenty divisions on the light wedge correspond to 15·5 divisions on the dense wedge, making the relation between the divisions on the light and dense wedges 0·7 to 1 respectively.

*Comparison between the Wedges.*

There being two wedges of different densities available for use, it was not only interesting to compare measures made with each of them, but it was also important, because, in case any accident should occur to one of them during the process of measuring hundreds of photographs, the work could be carried on with the other.

For this purpose selected lines in the spectrum of $\gamma$ Orionis, a spectrum with few but well-defined lines, were measured with each wedge by the same two observers.

Three measures were made of each line, the means of these only being given in the following table.

The numbers after the first column represent divisions and estimated tenths of divisions on the scales of the wedges.

| Line λ. | Edwards. | | | | Rimmer. | | | |
|---|---|---|---|---|---|---|---|---|
| | Light Wedge. | Dense Wedge. | Diff. L – D. | Residuals from Mean. | Light Wedge. | Dense Wedge. | Diff. L – D. | Residuals from Mean. |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| Hβ | 19·0 | 9·8 | 9·2 | +0·3 | 21·8 | 11·8 | 10·0 | –0·1 |
| 4472 | 18·0 | 8·0 | 10·0 | –0·5 | 20·3 | 10·0 | 10·3 | –0·4 |
| 4388 | 16·0 | 7·8 | 9·2 | +0·3 | 17·7 | 8·0 | 9·7 | +0·2 |
| Hγ | 19·3 | 9·8 | 9·5 | 0·0 | 21·5 | 10·9 | 10·6 | –0·7 |
| 4144 | 17·8 | 8·0 | 9·8 | –0·3 | 19·3 | 10·4 | 8·9 | +1·0 |
| 4121 | 14·3 | 5·3 | 9·0 | +0·5 | 17·3 | 7·6 | 9·7 | +0·2 |
| Hδ | 21·0 | 10·8 | 10·2 | –0·7 | 22·5 | 12·2 | 10·3 | –0·4 |
| 4026 | 17·3 | 7·0 | 10·3 | –0·8 | 18·7 | 9·8 | 8·9 | +1·0 |
| 4009 | 14·0 | 5·3 | 8·7 | +0·8 | 17·4 | 7·3 | 10·1 | –0·2 |
| Hε | 19·0 | 9·8 | 9·2 | +0·3 | 22·0 | 11·5 | 10·5 | –0·6 |
| Means | 17·6 | 8·2 | 9·5 | | 19·8 | 9·9 | 9·9 | |

Column 1 in the above table indicates the wave-lengths or names of the lines measured. Columns 2 and 6 give the measures of the various lines with the light wedge by the two observers. It will be seen that Mr. Rimmer's values are almost constantly larger than those of Mr. Edwards' by a mean amount of 2·2 wedge divisions. Similar remarks apply to the measures of the dense wedge in columns 3 and 7, only Mr. Rimmer's measures are here 1·7 divisions larger than those of Mr. Edwards'.

In spite, however, of this personal equation, the individual differences between the readings of the light and dense wedges, as shown in columns 4 and 8, by both observers, are in good agreement, the mean values in the two cases being 9·5 and 9·9 divisions for Mr. Edwards and Mr. Rimmer respectively. The residuals, as shown in columns 5 and 9, are one division, or less than one division, of the wedges. The

result of this inquiry shows that the light-wedge readings are in the mean 9·7 divisions more than those of the dense wedge.

The probable error of a single measure of the difference between the wedges is ±0·37 and ±0·41 divisions, and that for the mean difference of all the measures is ±0·12 and ±0·13 divisions for Mr. Edwards and Mr. Rimmer respectively.

### *Measures of the Differences of Intensities between Close Pairs of Spectral Lines.*

In order to form an idea of the accuracy of this method in determining the differences in intensities between close pairs of lines in a stellar spectrum, a series of measures of six selected pairs of lines in four stellar spectra were made. The negatives used were those obtained with the Frank McClean 12-inch objective-prism telescope, and belong to the series of negatives now being measured for parallax determinations.

The measures were made by the same two observers. The following table shows the stars used, the selected pairs of lines, and the measures by the two observers, each measure being the mean of five readings:—

| λ of Pairs. | α Cassiopeiæ. | | | β Herculis. | | | γ Cephei. | | | τ Ceti. | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Edwards. | Rimmer. | E – R. | Edwards. | Rimmer. | E – R. | Edwards. | Rimmer. | E – R. | Edwards. | Rimmer. | E - |
| 4227/4216 | 1·5 | 1·3 | +0·2 | 1·5 | 1·7 | –0·2 | 2·4 | 2·7 | –0·3 | 4·0 | 4·3 | – |
| 4216/4250 | 3·9 | 4·0 | –0·1 | 3·5 | 3·5 | 0·0 | 2·2 | 2·5 | –0·3 | 0·4 | 0·1 | + |
| 4227/Hγ | 3·0 | 3·3 | –0·3 | 2·5 | 2·6 | –0·1 | 4·7 | 5·0 | –0·3 | 1·7 | 1·7 | |
| 4326/4272 | 1·7 | 1·5 | +0·2 | 2·5 | 3·0 | –0·5 | 1·0 | 0·6 | +0·4 | 1·3 | 1·7 | – |
| 4326/Hγ | 1·8 | 1·5 | +0·3 | 1·5 | 1·9 | –0·4 | 2·5 | 2·6 | –0·1 | 1·0 | 1·3 | – |
| Hγ/4352 | 1·3 | 1·4 | –0·1 | 1·0 | 1·0 | 0·0 | 0·5 | 0·2 | +0·3 | 1·6 | 2·0 | – |
| Means | 2·2 | 2·1 | ... | 2·1 | 2·3 | ... | 2·2 | 2·3 | ... | 1·6 | 1·8 | . |

By examining the differences between the measures of the two observers, it will be seen that they are all equal to, or less than, 0·4 of a division, with one exception. This exception occurs in the measurement of the fourth pair, the difference being –0·5.

A reference to this pair on a large dispersion spectrum shows that while λ4326 is a good line to measure, λ4272 is not satisfactory, as it has on its red side two lines close to it due to Fe and Cr. This composite nature, more or less blended on a negative of smaller dispersion, most probably accounts for the larger values recorded, and indicates that such a pair of lines should not have been used. Neglecting these

values and remembering that tenths of a division are only estimated on the wedge scale, the resulting measures are very good.

## *Interconversion of the Wedge Divisions.*

By drawing a line, as shown in fig. 3, between the zero of the wedge divisions and the point where 20 on the light wedge meets division 15·5 on the dense wedge, any point on this line gives the relation between a division on the light wedge and the corresponding division on the dense wedge. Thus the differences in intensities between two lines measured on one wedge can be rapidly converted into those on the other.

To test this, the measured pairs of lines in the four stars referred to above were now measured similarly with the light wedge. These latter measures were then converted to the dense-wedge divisions by means of the above-described scale. The means of the same two observers in each case were compared, and the results are shown in the following table :—

| α Cassiopeiæ. | | | β Herculis. | | | γ Cephei. | | | τ Ceti. | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Observed. | Reduced. | O – R. | Observed. | Reduced. | O – R. | Observed. | Reduced. | O – R. | Observed. | Reduced. | O – R. |
| 1·4 | 1·7 | –0·3 | 1·6 | 1·6 | 0·0 | 2·55 | 2·5 | +0·05 | 4·15 | 4·2 | –0·05 |
| 3·95 | 3·6 | +0·35 | 3·5 | 3·5 | 0·0 | 2·35 | 2·2 | +0·15 | 0·25 | 0·15 | +0·1 |
| 3·15 | 2·6 | +0·55 | 2·55 | 2·4 | +0·15 | 4·85 | 4·4 | +0·45 | 1·7 | 1·8 | –0·1 |
| 1·6 | 1·3 | +0·3 | 2·75 | 2·7 | +0·05 | 1·3 | 0·9 | +0·4 | 1·5 | 1·8 | –0·3 |
| 1·65 | 1·3 | +0·35 | 1·7 | 1·5 | +0·2 | 2·55 | 2·4 | +0·15 | 1·15 | 1·2 | –0·05 |
| 1·35 | 1·5 | –0·15 | 1·0 | 0·8 | +0·2 | 0·35 | 0·3 | +0·05 | 1·8 | 1·6 | +0·2 |

The residuals shown in the columns under the heading O – R are very satisfactory, the largest being only 0·55. The mean value of all the residuals, regardless of sign, is 0·19 divisions, a quantity well within the error of measurement. The conclusion to be derived is that, should the necessity arise to convert one scale into another, the conversion diagram given above presents a very accurate method.

## *Effect of Errors in Measurement on the final Results.*

In the measurement of the differences in intensities between close pairs of lines it is found that ± 0·4 of a division is about the largest error that will enter into the final determinations of stellar classification and parallax from a *single* measure.

At the present time it is not possible to say how the error will affect the cases of stars of every spectrum type, because curves for each type are not available. It is possible, however, to state the case in

stars of F and K types, for these have now been determined at the Norman Lockyer Observatory.

In the case of F-type stars an error of $\pm 0 \cdot 5$ division in the wedge readings will produce an error of $\pm 0 \cdot 5$ in the absolute magnitude, and of about 25 per cent. in the parallax. For K-type stars the error in absolute magnitude would be $\pm 1 \cdot 0$, and in parallax about 50 per cent.

The determinations of the differences in intensities of the pairs of lines is, however, the *mean* of at least three sets of measures, and, further, three distinct pairs of lines are in general used for the determination of the absolute magnitude of each star. The probable errors in the final results are therefore very considerably reduced from those stated above.

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Correction to the Catalogue of William Herschel Papers, *Monthly Notices*, **78**, 548 :—

Part XI. of the "Journal," supposed to be lost, has recently been found at Observatory House, Slough, and has been added to the collection. It contains observations from May 19, 1787, to March 7, 1794, chiefly of planets and satellites.